Damage control thoracic surgery: What you need to know

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ABSTRACT: Damage control surgery in trauma prioritizes patient stabilization through an initial temporizing surgical approach to rapidly control hemorrhage and contamination, minimizing intraoperative time to allow for resuscitation and the correction of hypothermia, coagulopathy, and acidosis in the intensive care unit. This is followed by definitive repair of injuries once physiological parameters have improved. While damage control techniques for traumatic intra-abdominal and extremity injuries are well established and frequently utilized, the same cannot be said for damage control thoracic surgery. The complexity of thoracic injuries, the intricate decision making process, the level of surgical expertise required, and potential complications make damage control thoracic surgery particularly challenging. However, advances in surgical techniques, improvements in perioperative care, and the emergence of adjuncts such as extracorporeal membrane oxygenation have significantly enhanced decision making and underscored the importance of timely and decisive intervention in damage control thoracic surgery to optimize patient outcomes. This review aims to provide a comprehensive overview of damage control thoracic surgery, detailing the principles, indications, operative techniques, perioperative management, and the integration of advanced therapies to improve outcomes in patients with severe thoracic injuries. (*J Trauma Acute Care Surg.* 2025;98: 11–19. Copyright © 2024 Wolters Kluwer Health, Inc. All rights reserved.)

KEY WORDS: Damage control; thoracic surgery; ECMO; cardiopulmonary bypass.

HISTORY, PRINCIPLES, AND INDICATION FOR DAMAGE CONTROL THORACIC SURGERY

Expedited control of surgical hemorrhage and contamination are the central principles of damage control for penetrating abdominal trauma (DCAS) defined in the early 1990's in physiologically compromised patients.[1] Nonsurgical bleeding is controlled with various hemostatic techniques, usually packing, and gastrointestinal reconstruction is deferred. After resuscitation and stabilization in the intensive care unit (ICU), the patient returns to the operating room (OR) for unpacking and the definitive completion of their surgical care.[1] The use of DCAS resulted in improved survival and those principles were subsequently applied to vascular surgery, emergency general, and orthopedics.[2–5] The use of damage control for thoracic injury (DCTS) was slower to be adopted, likely because thoracotomy is less frequent than laparotomy in trauma, concern that cardiac tamponade or hypoventilation may arise from thoracic packing, and lack of familiarity among some surgeons with the indications and techniques of DCTS.[6–8]

While damage control principles are consistent across the surgical disciplines, DCTS is distinct from DCAS in two ways. First, there are a variety of operative approaches to explore the thoracic cavity compared to the standard laparotomy incision used to explore the abdominal cavity. Second, the need for contamination control is uncommon, as esophageal injuries are rare. While the literature is sparse regarding outcomes, a recent systematic review by Douglas et al. suggested that DCTS is associated with improved survival.[8]

Although there are no rigidly defined indications for DCTS, certain physiologic parameters[7] and injury/anatomic characteristics[7,9,10] have been identified that influence the decision to proceed with a damage control approach (Table 1).

INTUBATION, INCISION SELECTION, AND POSITIONING

While a double-lumen endotracheal tube can be very helpful in DCTS, a single-lumen tube is usually used because patient instability does not allow the time for double-lumen tube placement. The endotracheal tube can be advanced into the main stem bronchus to isolate the other lung, or an endobronchial blocker can be placed. Temporarily holding ventilation and manual compression of the lung parenchyma can improve exposure. A double-lumen tube can be used in patients who are temporarily stabilized or in centers that are facile with emergent placement.[10]

There are several incisions used for thoracic exploration for DCTS (Table 2). An anterolateral thoracotomy is the most often used incision in an unstable patient. Placing a bump of 30 degrees and extending the ipsilateral arm improve the exposure. The incision is rapid, does not require a sternal saw, and is familiar to most trauma surgeons. It can be extended across the chest and converted to a clamshell thoracotomy for enhanced exposure. The trapdoor incision has generally been abandoned as a sternotomy, and a supraclavicular incision provides excellent exposure of the aortic arch and the proximal left subclavian artery. A posterolateral thoracotomy incision is not suitable for a hemodynamically unstable patient, as lateral positioning may increase hemodynamic instability, is of limited versatility, and cannot be extended. However, it is the preferred approach for an

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TABLE 1. Indications for Damage-Control Thoracic Surgery (1–3)

Physiologic Parameters	Injury Characteristics
Arterial pH < 7.2 lactate >5 mmol/L	Resuscitative thoracotomy with aortic occlusion
Base deficit >15 mEq/L	Hemodynamic instability and a blunt or penetrating nonhilar injury requiring lung resection
Lactate >5 mmol/L	Hemodynamic instability and irreparable hilar/mainstem bronchus injury
Hypothermia (<34°C)	Pneumonectomy
Coagulopathy	Repair of vascular structures
Massive transfusion	The need to place packs over the thoracic wall and/or the chest cavity to control coagulopathic bleeding
	Development of thoracic compartment syndrome during an attempt at chest closure
	Concomitant nonthoracic injuries requiring surgical intervention (craniotomy/craniectomy, damage-control laparotomy, and major intra-abdominal or lower extremity vascular repair)

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intrathoracic aerodigestive injury in hemodynamically stable patients. Median sternotomy is indicated if anterior mediastinal injury is suspected. Subclavian and carotid exposure can be obtained by extending the sternotomy using a periclavicular or neck incision. It can also be extended for a laparotomy.

Given that no single incision will allow access to all compartments of the thoracic cavity, in the setting of DCTS, the selected incision must be rapid and versatile, must provide adequate exposure, and be based on the surgeon's experience.[11,12] Often, the initial incision is selected based on the best estimate of injury anatomy. If the incision does not provide adequate exposure, it should be extended, or a second incision should be performed. At our institution, we never hesitate to extend the thoracotomy to a clamshell as the additional exposure facilitates cardiac and complex thoracic repair.[7]

DAMAGE-CONTROL TECHNIQUES FOR INTRATHORACIC INJURIES: THE INDEX OPERATION

Lung Injuries

Nonanatomic Lung-Sparing Resections

The vast majority of operative lung injuries can be managed with lung-sparing primary repair or nonanatomic resections. This provides rapid control of hemorrhage, shorter operative time, and reduced intraoperative blood loss, all of which are associated with decreased mortality (Fig. 1).[10,13–15]

Nonanatomic techniques include pneumonorrhaphy, tractotomy, and wedge resection. Pneumonorrhaphy and/or wedge resection are the simplest techniques and should be used for the management of peripheral superficial pulmonary injuries.[16] Concomitant severe thoracic or extrathoracic injuries are then managed using damage-control principles. Tractotomy is the most rapid method to control deep nonhilar pulmonary parenchymal bleeding and is our "go to" maneuver in DCTS. This is achieved through opening the tract with a surgical stapler. We prefer using the universal staples with multiple loads, as needed. After obtaining hemostasis with suture, we often run a suture under the staples for additional hemostasis, apply fibrin sealant to treat nonsurgically raw surface bleeding, and close the lung by suturing the staple lines together. Bioglue (Artivoan, Kennesaw, GA) is useful if there is persistent bleeding.[17] Suture closure of deep wounds to the lung with significant bleeding or air leaks should be avoided to prevent air embolism, continued bleeding, and subsequent infection.

Anatomic Resection

If lung-sparing attempts are not indicated or fail, a lobectomy or pneumonectomy is required.[18,19] A lobectomy is reserved for central injuries and extensive but focal parenchymal damage.

TABLE 2. Thoracic Surgery Incision Techniques

Incision	Anatomical Exposure	Positioning
Median sternotomy	Heart, ascending aorta, superior vena cava, pulmonary vessels, both lungs, mid to distal trachea, and left mainstem bronchus	Supine with arm extended
Left anterolateral thoracotomy	Descending aorta for cross clamping, left lung, pulmonary hilum, and pericardium with limited cardiac exposure	Supine with a 20–30° bump under the back and extending the ipsilateral arm, allowing the incision to be carried down to the axilla
Right anterolateral thoracotomy	The right lung and pulmonary hilum	Similar to above
Trap door thoracotomy	Proximal left subclavian artery	Similar to anterolateral thoracotomy
Clamshell thoracotomy	Bilateral lung injuries, anterior cardiac or superior mediastinal vascular injuries (aortic arch, brachiocephalic trunk, left common carotid, and left subclavian arteries, superior vena cava, brachiocephalic veins, and the arch of azygos)	Similar to anterolateral thoracotomy
Posterolateral thoracotomy	Descending aorta, thoracic esophagus, distal trachea, and the main stem bronchi	Lateral decubitus position with extended arm

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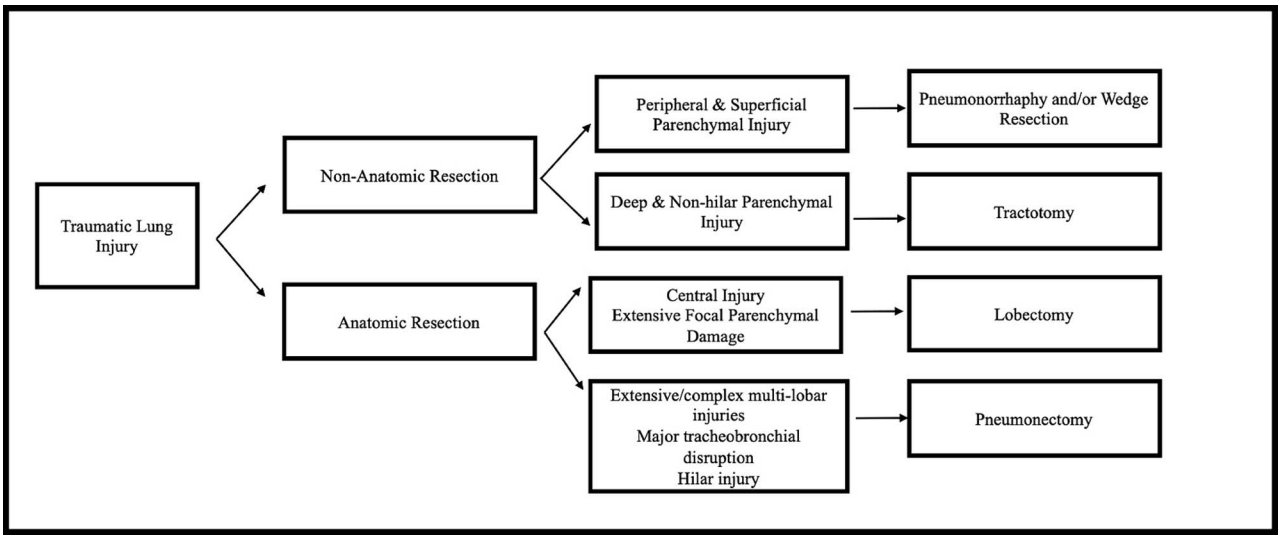

Figure 1. Decision-making process and techniques for managing lung injuries.

The amount of time required for an anatomic lobectomy does not make it suitable for use in DCTS. Rushing when isolating the vascular structures risks injury to the more central vasculature. In DCTS, if a lobectomy is indicated, the entire lobe and pulmonary artery, vein, and bronchus should be rapidly resected en masse with a surgical stapler. At our institution, we are more likely to perform a nonanatomic lung resection, removing only the damaged lung. Leaving a portion of the lung behind, even if it is not well perfused or aerated, is acceptable. Completion lobectomy can be performed during the take back.

A pneumonectomy is reserved for extensive/complex multilobar injuries, major tracheobronchial disruption, and hilar injury. Temporary control of major hilar injury/hemorrhage can be achieved with manual hilar compression, clamping the hilum en masse and the hilar twist. The hilar twist is achieved through takedown of the inferior pulmonary ligament and rotating the lower lobe up, twisting the major pulmonary vasculature. While hilar twist can be effective, performing the pneumonectomy with the lung twisted is difficult. Use of a vascular clamp can fail, as the rigid airway does not allow the clamp to occlude the vessels. Thus, we opt for manual control. Proximal hilar injuries may require opening of the pericardium to achieve vascular control.[16] All these techniques can increase right ventricular (RV) afterload causing acute heart failure or fibrillation in the acidotic and ischemic heart. When used, rapid control of the injury with early release minimizes this risk and also minimizes air embolism.[20]

While a pneumonectomy is rarely needed, it is a viable option for patients in extremis.[18] The decision to perform a pneumonectomy must be made quickly. Continued blood loss with acidosis and hypotension means that the patient will tolerate hilar vascular ligature even less well. While individual ligation of the pulmonary artery, vein, and bronchus is preferred, this can be difficult to achieve in the acute setting. Therefore, our practice has been to ligate the hilum en masse using a thoracoabdominal stapler. Once the lung is removed, a Prolene stitch is run under the staples to reinforce the staple line. We almost always use damage-control techniques after a pneumonectomy, and bronchial stump reinforcement is performed at the takeback. While intercostal muscle is attractive, it is rarely robust enough. A flap of pericardium is a good alternative.

Postpneumonectomy complications include cardiac arrythmias (atrial fibrillation/flutter), cardiac herniation, bronchopleural fistula, pneumonia, RV failure, acute respiratory distress syndrome, and pulmonary edema.[21] Mortality postpneumonectomy has been reported to be between 50% and 100%.[18] Intraoperative mortality is due to uncontrollable hemorrhage, RV failure, or air embolism. Postoperative mortality is due to respiratory insufficiency, a sudden increase in pulmonary vascular resistance, and associated RV failure causing refractory shock. A National Trauma Database study by Matsushima et al.[19] of 261 patients requiring a pneumonectomy, over 7 years, reported a 60% mortality rate. The majority of the deaths were within the first 24 hours postoperative in patients presenting with concomitant traumatic brain injury. However, patients who survived the first 24-hours were more likely to survive to hospital discharge.[19]

Extracorporeal Membrane Oxygenation Support Postpneumonectomy

There are several case reports of the use of extracorporeal membrane oxygenation (ECMO) postpneumonectomy with DCTS.[18,21–24] For those with acute RV failure due to acute hypoxia and/or increased pulmonary vascular resistance, venovenous (VV) ECMO can be effective. For those with RV injury or RV failure with concomitant left ventricular failure, venoarterial (VA) ECMO may be preferable. Both modalities support the RV by reducing preload, reducing RV wall tension, and delivering oxygenated blood to the coronaries.[25,26]

VV-ECMO reduces pulmonary artery pressures, uses minimal ventilator driving pressure, improves cardiac index, and reduces central venous pressure.[27] Right ventricular failure can then be managed with inotropic support or administering pulmonary vasodilators.[25,27] VV-ECMO decreases hypoxia and hypercarbic-mediated pulmonary vasoconstriction and improves $PaCO_2$ and pH, resulting in increased cardiac contractility.[25,28] VV-ECMO offers anatomic benefits over

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VA-ECMO, namely, minimal risks of limb ischemia or arterial air embolism because the arterial system is not accessed.[25] In addition, VV-ECMO has a lower risk of bleeding. As such, VV-ECMO is recommended as an initial strategy in patients with impending or active RV failure due to hypoxemic respiratory failure, even in the setting of shock.[25] In our experience, postpneumonectomy patients placed on ECMO experience a reduction in mortality,[18] and therefore, every patient is placed on VV-ECMO immediately after pneumonectomy to offload the RV.

Cardiac Injuries

When repairing the heart in a DCTS setting, rapid identification of injury anatomy and repair are essential. Several techniques can be used to achieve temporary control of cardiac hemorrhage, facilitating cardiac repair as part of DCTS. For smaller injuries, direct digital control may be adequate, with care taken not to increase the size of the wound with excessive pressure. In the setting of multiple cardiac lacerations, stapling can be used. Unfortunately, modern staplers have smaller staples than the earlier versions, making this less effective. In addition, the contour of the newer stapler makes visualizing the injury and precise staple placement more difficult.

For larger wounds, not amenable to either direct pressure or stapling, balloon occlusion with a clamped Foley catheter may be beneficial. The balloon is inflated with saline and gently withdrawn against the myocardial wall. Excessive traction should be avoided because it could enlarge the myocardial wound.[20,29] At our institution, we virtually never use this technique, as we fear making the injury larger and repair with the balloon in situ is almost impossible. Near total inflow occlusion with the Sauerbruch's maneuver can be achieved by placing the third and fourth finger behind the right atrium and compressing it between the second and third finger; vascular clamps may be added to the inferior and superior vena cava if needed because of injury pattern. This maneuver is used for large posterior injuries, left atrial injuries, and injuries that occur in the very lateral aspect of the right atrium and to the superior and inferior atriocaval junction. This maneuver is poorly tolerated in the acidotic, hypotensive patient and may result in rapid deterioration/cardiac arrest. However, brief application allows identification and positioning of a vascular clamp or series of intestinal allis clamps to control the injury may be lifesaving.[20]

Surgical Technique Considerations

The methods used for cardiac repair do not differ significantly when applied in a DCTS setting. Proper selection of suture type and size of needle is important. In our practice, polypropylene sutures and pledgets are typically used, particularly for ventricular repairs. The needle driver is positioned at the very back of the needle to ensure that the needle enters the myocardium at right angles, using the entire curve of the needle to achieve a substantial bite of the tissue. It is crucial to tie flat smooth knots to ensure a secure repair, which is facilitated by relative hypotension.

When using DCTS, a running suture is attractive to temporize a cardiac injury. It is essential to ensure that the repair is secure. Often, if the patient remains hypotensive with weak cardiac contractility, the repair may seem adequate. However, as the heart recovers and contractions become more forceful, the heart will tear through an inadequate repair suture, leading to significant hemorrhage. Recovering from this is difficult, to say the least. Therefore, we prefer to buttress the remaining suture with a row of pledgeted interrupted suture. Use of Bioglue (Artivoan, Kennesaw, GA) can be helpful to buttress tenuous repair preventing recurrent bleeding.

Our group recently published considerations for particular surgical techniques for repairing the cardiac injuries in a review article. We refer the readers to the article titled "Treatment of penetrating cardiac wound for the general surgeon on call" for an in-depth discussion of cardiac repair.[30]

Pericardial Closure

Pericardial closure minimizes postoperative retrosternal adhesions and prevents lateral cardiac herniation. However, in the DCTS setting, closing the pericardium has the potential to lead to iatrogenic tamponade due to myocardial edema from direct injury or resuscitation. Given this, the risk usually outweighs the benefits. Therefore, closure of the pericardium is not warranted in the acute setting.[29]

Cardiopulmonary Bypass and Extracorporeal Cardiopulmonary Resuscitation/VA-ECMO as Adjuncts to Managing Cardiac Injuries

Urgent cardiopulmonary bypass (CPB) can be used in selected patients with penetrating cardiac injuries. Anatomic considerations include injuries to the coronaries, injuries that cannot be adequately exposed or repaired without CPB (posterior injuries/multiple chamber injuries/valve injuries), and injuries causing substantial cardiac dysfunction, arrhythmias, or impending intractable heart failure despite attempts at repair.[29,31,32]

In DCTS, diversion of the blood flow from the injured heart, reducing ongoing hemorrhage, and support of peripheral and cerebral perfusion allow for thorough inspection and exposure of the heart, as well as definitive myocardial repair within a bloodless field. Concomitantly, hypothermia, hypovolemia, hypoxemia, acidosis, and coagulopathy can be corrected.[32,33] Coagulopathy from systemic heparinization during CPB, especially in patients with multiple injuries, can be obviated to some extent with heparin-bonded circuits.[29]

It is unclear whether there is a survival benefit among trauma patients treated with urgent CPB.[31,34,35] A recent National Trauma Data Bank study by Johnson et al.[33] of 319 propensity-matched trauma patients sustaining cardiothoracic injuries, who underwent repair within the first 24 hours of admission with and without the use of CPB, showed a mortality benefit with CPB use. Cardiopulmonary bypass was primarily used in cases requiring vascular and complex cardiac repair.[32]

Extracorporeal cardiopulmonary resuscitation/VA-ECMO provides full hemodynamic support in shock that is refractory to conventional therapy and effectively manages gas exchange and perfusion while stabilizing the patients without the need for high-dose inotropes/vasopressors. Moreover, in trauma patients, VA-ECMO provides hemodynamic support, allowing for adequate time for definitive hemostatic surgery and further treatment.[37] Therefore, it can and should be used in the DCTS management of selected cardiac injuries as a bridge to intervention[37]

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and in the setting of cardiogenic shock due to myocardial stunning as a bridge to recovery.[37,38]

Several case reports/series detailing use of VA-ECMO as a damage-control technique have been published, with some studies showing a mortality benefit with early use.[37–41] A study by Huh et al.[40] used extracorporeal cardiopulmonary resuscitation/VA-ECMO for the management of five patients with cardiac chamber rupture who experienced a brief cardiac arrest (≤10 minutes) as a bridge to definitive repair. All five patients were weaned off of VA-ECMO postrepair and survived to discharge.[39]

Vascular Injuries

Thoracic vascular trauma can present a significant challenge. The relative inaccessibility of the vasculature, potential exsanguinating hemorrhage, and the lack of surgeon experience all contribute to the high mortality. While thoracic vascular trauma accounts for <5% of traumatic vascular injuries, the mortality rate is >50%.[41]

Management of Venous Injuries

Although thoracic venous injuries may be repaired, it can be time-consuming and often result in venous thrombosis and possible embolization. In DCTS, most thoracic venous injuries can be ligated if simple repair is not possible. Exceptions are the superior and inferior vena cava, which must be repaired without lumen compromise.[41]

Management of Arterial Injuries

While the intercostal arteries are managed with ligation, the remaining thoracic arteries require repair. Primary repair is the treatment of choice if possible. The more complex injuries often require resection with end-to-end interposition grafting (Polytetraflouroethylene (PTFE) graft). However, in DCTS, performing arterial reconstruction is ill advised. Instead, perfusion should be re-established using a temporary intravascular shunt. Definitive repair should only take place once resuscitation is completed, and normal physiologic parameters are restored. DCTS with a temporary intravascular shunt is ideal for all branches of the aortic arch with the exception of injuries to the ascending or proximal descending aorta. In these cases, temporary bleeding control with or without CPB may be the only feasible management option.[12,41]

When selecting the shunt size for temporary bypass, the largest size of shunt that fits into the injured vessel should be used. This will maximize distal blood flow. Commercially made shunts should not be trimmed, as the edges are smooth and designed to avoid trauma to the intima of the artery. Improvised shunts (chest tubes, intravenous tubing, feeding tubes) should be left long, with redundant length in both the proximal and distal vessel. This will reduce the risk of inadvertent dislodgement. The maximum length of time that a vascular shunt can remain in situ is unknown.[12] We perform definitive repair as soon as the patient's physiology and other circumstances allow.

Hybrid (Open and Endovascular) Methods for Vascular Injury Management

With the expanding role of catheter-based therapy, a combination of open and endovascular approaches should be considered in DCTS in centers with immediate access and the necessary expertise. Endovascular balloon occlusion is a sophisticated inflow control option, allowing control without extensive dissection in challenging anatomic locations. This is particularly helpful when treating proximal subclavian and common carotid artery injuries.[41]

Another application to consider is the use of resuscitative balloon occlusion of the aorta (REBOA) as an intraoperative adjunct. Thoracic trauma has traditionally been a contraindication to REBOA use, as REBOA may increase bleeding proximal to the aortic occlusion and paradoxically hinder rapid and efficient hemorrhage control.[42]

However, two recent studies from the trauma group in Cali, Colombia, have highlighted the effectiveness of using REBOA as an intraoperative adjunct for noncompressible thoracic hemorrhage. In 2018, the group provided proof of concept in seven patients who presented with penetrating thoracic injuries in the setting of hemodynamic instability, acidosis, and massive transfusion. A zone 1 REBOA was placed in the OR prior to operative repair of intrathoracic injuries via median sternotomy. Resuscitative balloon occlusion of the aorta occlusion time ranged from 20 to 60 minutes. Six of the seven patients survived.[42] Subsequently, the group published an extended experience involving 56 patients with both penetrating (37) and blunt thoracic trauma (19), where a zone 1 REBOA was used as an adjunct to median sternotomy or thoracotomy for intraoperative repair. The overall survival rate was 65.2%.[43]

Aerodigestive Injuries

Aerodigestive injuries are extremely rare. At our institution, we managed 95 patients between 2000 and 2020, with an overall mortality rate of 10%. Five patients presented in extremis and were managed using preoperative VV-ECMO as a bridge to definitive repair. Sixty-six airway injuries were repaired surgically, and two were definitively treated with endobronchial stents. There were 27 associated major vascular injuries (29%), 14 patients required laparotomy for concomitant abdominal injury, and 10 had severe traumatic brain injury. The majority of damage-control repairs of tracheobronchial injuries were performed through a median sternotomy because of the frequent presence of concomitant vascular injuries.[44,45]

Tracheobronchial Injuries

Initial airway management is of paramount importance in the setting of tracheobronchial injuries. Airway management should be conducted by the senior most member of the airway team. Various methods of management can be successful, but good visualization of the upper airway structures is of the utmost importance. In most cases, endotracheal intubation using a Bougie, as needed, is sufficient. Flexible bronchoscopy, with care taken not to convert a partial tracheal injury into a complete disruption, can help. This allows for (1) identification of the level and degree of injury and (2) positioning of the endotracheal tube cuff either beyond the level of the injury or in the uninjured main bronchus, allowing for single lung ventilation.[44] Occasionally, a surgical airway often as the level of injury is needed.

In the DCTS setting, a median sternotomy is the incision of choice because it allows access to the distal airway. The blood supply to the trachea is segmental, so mobilization should be

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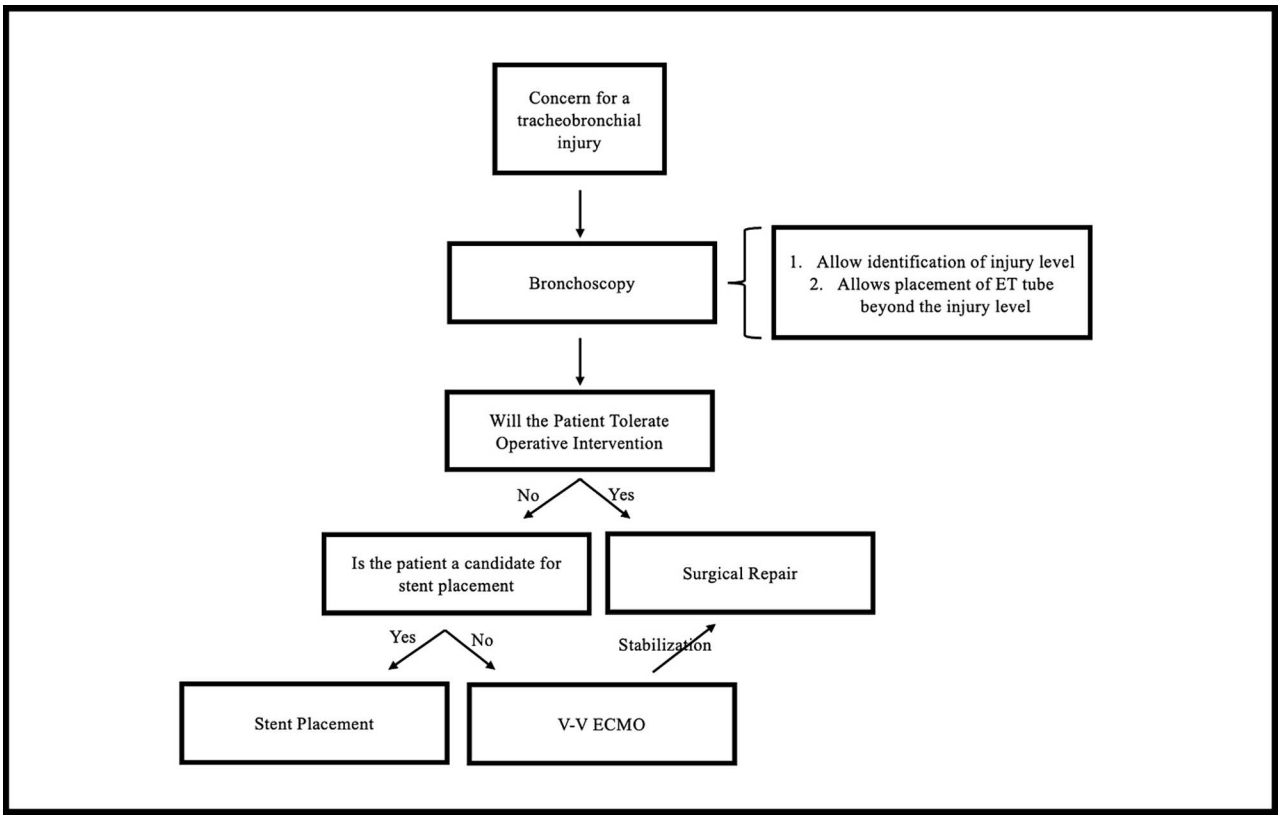

Figure 2. Management of tracheobronchial injuries.

limited to prevent suture line ischemia. Surgical repair requires debridement of the devitalized tissue and repair with a single layer of interrupted absorbable monofilament sutures.[44,45]

Endobronchial stents are rarely used in trauma and are only used as a temporizing technique.[46] At our institution, endotracheal stents have been used twice in patients with severe airway injury and a concomitant traumatic brain injury. Given the risk of hypotension, hypoxia, hypercarbia, and intracranial hypertension associated with operative repair, stenting was deemed to be a safer option for management. Interval bronchoscopies revealed proper airway healing, and the stents were removed at 22 and 78 days without the need for surgical intervention.[45]

In cases where the patient presents with profound acidosis with associated hypercapnia and hypercarbia that are refractory to conventional ventilation, VV-ECMO can be used as a bridge to repair for tracheobronchial injuries (Fig. 2).[45,47]

Esophageal Injuries

Esophageal injuries are rare, almost entirely the result of penetrating trauma, and have serious complications and high mortality. Morbidity and mortality are associated with a thoracic location, combined injuries, delay to definitive repair, and extent of esophageal resection.[45,48,49] Injury to the thoracic esophagus is often associated with concomitant tracheal and great vessel injuries. Therefore, the primary aim of DCTS is to control contamination and provide wide drainage with or without definitive repair. The choice of repair depends on the magnitude of esophageal destruction, often in a hemodynamically unstable patient.

If the esophageal injury is small and amenable to rapid primary repair, this is achieved through the debridement of nonviable tissue and a two-layer repair over a nasogastric tube or esophageal dilator. The esophagus can be widely mobilized because it is a rich submucosal blood supply. The repair should be covered later with an intercostal muscle, pleural, pericardial, or omental flap postresuscitation to prevent suture failure. Wide mediastinal drainage, antibiotics, strict nil per os, and distal feeding access are essential.

In cases of significant contamination or extensive destruction rendering primary repair impactable, management options include (1) repair of the esophagus over a large T-tube creating a controlled esophagocutaneous fistula; (2) wide drainage of the area with thoracostomy tubes; and (3) complete diversion, which involves the creation of a side-cervical esophagostomy, a gastrojejunostomy feeding tube, and debridement and drainage of the distal esophagus.[44,48] Since mortality increases with the extent of esophageal resection, lesser procedures should be strongly considered.[49] At our institution, we have successfully managed these destructive lesions with retrograde drainage via transgastric tubes, which then exit the patient's abdominal wall in combination with nasogastric tube drainage and exterior drainage via thoracostomy tubes and closed suction drains.[44] Delayed esophageal reconstruction was performed with primary anastomosis, and no cervical esophagostomy was used.

Given the limitations of posterolateral thoracotomy and the frequent presence of concomitant intrathoracic injuries, an

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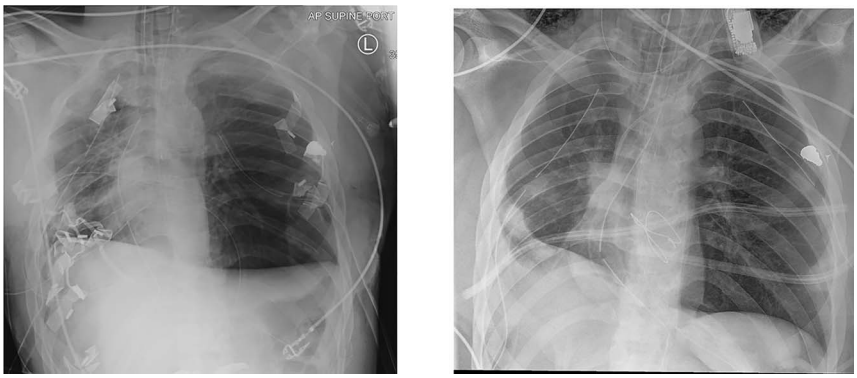

Figure 3. Radiographic imaging of thoracic cavity packing and subsequent packing removal.

anterolateral thoracotomy is the preferred incision in DCTS. Distal esophageal injuries can be accessed through a left anterolateral thoracotomy along the fourth to sixth intercostal spaces, and upper/mid esophageal injuries can be accessed through a right anterolateral thoracotomy. For those with combined tracheal and esophageal injuries, each injury is repaired separately, and muscle should be interposed between the suture lines when the patient is stabilized. Muscle interposition is also used for combined vascular and aerodigestive injuries.

Management of the Open Chest

Intrathoracic packing

There were theoretical concerns about the potential impact of thoracic packing on impaired cardiac function and increased peak airway pressure, resulting in impaired cardiopulmonary function.[50–56] Clinically, this has not been proven to be an issue.[7,50,51,56] Although the available literature consists of case reports and small series, cardiac and ventilatory functions have not been found to be compromised by thoracic cavity packing for bleeding control in DCTS.[51] In fact, proper packing is often associated with an improvement in hemodynamics when occurring in conjunction with adequate resuscitation.[50] When packing the chest, it is prudent to ensure that the packs are placed in the lateral, posterior, and apical thoracic recesses, thereby minimizing direct compression of the heart and lungs (Fig. 3).

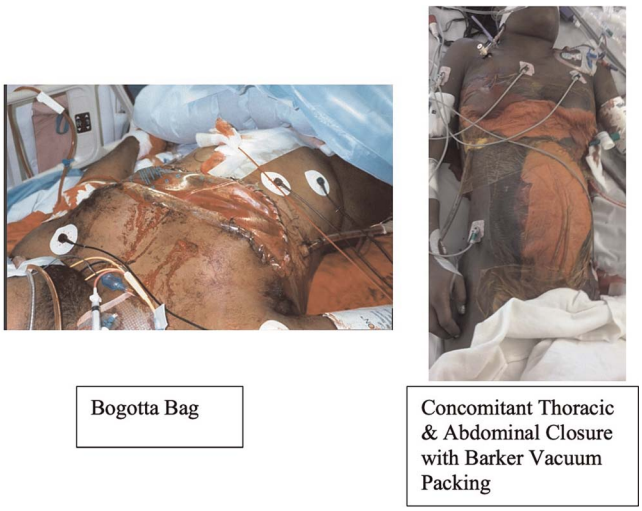

Figure 4. Temporary thoracic closure techniques.

Temporary closure techniques

There is no consensus on the most effective temporary closure techniques for DCTS.

In addition, similar to intrathoracic packing, concerns exist regarding the effect of temporary closure on cardiac function and intrathoracic pressure. Several temporary closure techniques have been described in the last two decades, often mimicking those used in DCAS, and include skin closure only,[56] Bogota bag,[55,57] Barker vacuum packing[58] (Fig. 4), and negative pressure wound vacuum devices.[50] These techniques are often paired with pleural drains and thoracostomy tubes to facilitate the drainage of both fluid and air.

A recent contemporary application to temporary chest closure is the utilization of the Abthera Advance Open Abdomen Dressing, which has become our preferred strategy.[59] Similar to its use in the open abdomen, the fenestrated visceral protective layer is cut to fit the thoracic cavity, the Abthera Advance perforated foam is applied over the protective layer, and the adhesive sheets are applied to seal the dressing. The negative pressure wound vacuum device is set at 50 to 75 mm Hg. An apical and basal thoracostomy tube, often 28 Fr, is also placed in the thoracic cavity.

POSTOPERATIVE MANAGEMENT IN THE INTENSIVE CARE UNIT

Since DCTS is infrequent and the available literature is sparse, no superior treatment options have been identified that dictate postoperative care. However, the focus should be on balancing resuscitation in an often hypovolemic, bleeding, and multiply injured patient with cardiopulmonary protection by preventing over resuscitation and volume overload. This should begin in the OR through effective communication with the anesthesia team to establish acute resuscitation goals, including using a balanced transfusion approach over crystalloid administration and early initiation of inotropes for cardiac support. When possible, using transesophageal echocardiography prior to leaving the OR to ascertain cardiac function and potential intracardiac injuries is often beneficial.

Over the years, our ICU care has evolved to focus on (1) hemodynamic monitoring using the pulmonary artery catheter

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and/or frequent intensivist-performed echocardiography to optimize fluid management and assess cardiac function. In the postpneumonectomy patient, frequent focused rapid echocardiography evaluations focus to assess volume status and RV function to prevent or mitigate RV failure and pulmonary hypertension. Over the years, our ICU care has evolved to focus on: 1) hemodynamic monitoring using the pulmonary artery catheter and/or frequent intensivist performed echocardiography to optimize fluid management and assess cardiac function. In the post-pneumonectomy patient, frequent focused rapid echocardiography evaluations focus to assess volume status and RV function to prevent or mitigate RV failure and pulmonary hypertension. 2) extremely judicious volume resuscitation, augmenting cardiac function with epinephrine and milrinone, promoting pulmonary vasodilation with epoprostenol, aggressive diuresis with intravenous diuretics or continuous renal replacement therapy, utilizing lung protective ventilator modalities, and early and aggressive initiation of VV-ECMO or VA-ECMO in the setting of concomitant cardiac and pulmonary dysfunction.

DEFINITIVE CLOSURE

Once physiological derangements have been correct, the patient is returned to the OR for definitive repair and chest closure, if possible. The thoracic cavity is thoroughly irrigated, and all previously placed drains are replaced. Standard techniques are used to close both sternotomy and thoracotomy incisions. For the clamshell incision, we recommend a lateral to medial closure approach, with close communication with anesthesia and transesophageal echocardiography to monitor and avoid the development of thoracic compartment syndrome during the closure. At our institution, we routinely use transesophageal echocardiography during DCTS incision closures, especially when a patient remains on vasopressors/inotropes, as our experience has been that these patients exhibit tamponade physiology before any hemodynamic changes are detected.

CONCLUSION

DCTS uses the same principles described for DCAS over 30 years ago. Either technique should only be used in patients critically ill and with physiological exhaustion. Overuse of the technique in patients who are only moderately injured almost certainly does not improve outcome and may make it worse. Rapid control of surgical bleeding and control of contamination are the primary goals. Nonsurgical hemorrhage can be treated with a variety of hemostatic packing materials. After resuscitation and physiologic stabilization in the ICU, the patient should return to the OR for unpacking, re-exploration to avoid missing injuries, and definitive reconstruction and closure.

It is difficult to prove that DCTS saves lives. There are no set criteria for the use of DCTS, and indications and techniques may vary from institution to institution and even among surgeons within an institution. Patients treated with the DCTS are more severely injured than those treated with standard techniques. The reported mortality of 15% to 25% certainly seems quite good, considering the injury burden, degree of shock, and the operative procedures and resuscitation necessary.[7,50,56] DCTS has become standard practice at our institution in a selected group of patients.

Mechanical organ support, to augment cardiac and pulmonary function, has become much more common. VV-ECMO is now routinely used in patients with hypoxic respiratory failure to avoid the physiologic stress of high driving pressure and ventilator therapy and to augment RV function. In patients treated with DCTS, the use of VA-ECMO is less frequent, but its use is increasing. In our hands, these techniques are part of resuscitation in critically injured patients. Institutions who do not have these capabilities should consider early transfer to a center who can provide this level of care. Alternatively, the ECMO can be initiated at the referring center, making transport safer.

While the principles of damage control remain the same, its application and indications continue to evolve. We look forward to future work that will help all of us determine when damage control is indicated and the evolving role of mechanical support.

AUTHORSHIP

M.H.G., J.V.O., and T.M.S. contributed in the literature review, drafting and revision of the manuscript revision, and final approval of the manuscript.

DISCLOSURE

Conflicts of Interest: Author Disclosure forms have been supplied and are provided as Supplemental Digital Content (http://links.lww.com/TA/E10).

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